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The Study of Key Thermodynamic Parameters Effects on the Performance of a Flash Steam

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Abstract: Geothermal energy is known today as one of the alternative renewable energy sources which has proven itself technically and economically to be feasible. It is commercially available to the public as a non pollutant electric power source. In 2005, over 15 countries started developing geothermal power production. The International Geothermal Association (IGA) has predicted that by the year 2010 geothermal power will grow from 8,900 MW (in 2005) to over 13,500 MW. Based on the current data from the exploration wells in the Meshkin Shahr, the first geothermal power plant in the middle east with the output power of 5 MW will be installed in this area soon. One of the important issues in the operation of the geothermal power plants is to investigate the key thermodynamic parameters' effects on the power plant performance. A few of these parameters including the outlet fluid enthalpy from the well, pressure of the flash vessel, steam turbine inlet pressure, condenser pressure have direct influence on the geothermal power plant output power and efficiency. It is clear that one can achieve suitable and reliable operation by optimization of these parameters. This paper reviews the effect of above parameters on the flash steam cycle based on the thermodynamic

Keywords: Geothermal Power Plant, Flash Steam Cycle, Condenser Pressure, Power Potential, Geothermal Well

Introduction

Geothermal energy is a sustainable source used for electricity generation. Geothermal sources are on the earthquake belt of the world. In those areas the temperature gradient is more than 60ºC in a kilometer. These sources are fed by surface water. Reaching these sources is possible by drilling a well at depth 200 to 3000m. Fig.1 shows the schematic of a geothermal power plant. In these power plants the natural steam from the production wells or the hot water from a flash vessel, powers the turbine generator. The steam is condensed by the cooling water from the wet cooling tower and pumped down an injection well to sustain production

Fig.1 Schematic of geothermal power plant

There are three geothermal power plant technologies being used to convert hydrothermal fluids to electricity. The conversion technologies are dry steam, flash, and binary cycle. The type of conversion used depends on the state of the fluid (whether steam or water) and its temperature. Dry steam power plants systems were the first type of geothermal power generation plants built. They use the steam from the geothermal reservoir as it comes from wells, and route it directly through turbine/generator units to produce electricity. Flash steam plants are the most common type of geothermal power generation plants in operation today. They use water at temperatures greater than 182°C that is pumped under high pressure to the generation equipment at the surface. Binary cycle geothermal power generation plants differ from dry steam and flash steam systems as the water or steam from the geothermal reservoir never comes in contact with the turbine/generator units

Iran lies on the geothermal belt of the world. Iran is planning to build its first geothermal power plant. According to the latest research, Iran has very promising prospects for geothermal energy development in the Sabalan, Damavand, Khoy-Maku and Sahand regions [1-2]. At present, the priority is given to a project to design and install a geothermal power plant in Meshkin Shahr [2]. This geothermal site is located in the Moil valley on the western slopes of Mt. Sabalan close to the town of Meshkin Shahr, in the province of Ardabil in northwest Iran. Fig. 2 shows the Mt. Sabalan and the geothermal field. At present, 10,000 m drilling of the exploration wells has finished and the discharge testing is currently underway to make resource assessment, reservoir numerical model and feasibility study. Five exploration wells with the maximum depth of 3000 m are producing the geothermal fluid for the discharge test activities. Fig. 3 shows these exploration wells.

Fig. 2 The Mt. Sabalan and the geothermal field in the Moil valley

Fig. 3 The exploration wells in Meshkin Shahr field

After a discharge test is finished, one may obtain the required information for preparing tenders for a small wellhead power plant (five to ten MWe) and production wells. According to the latest research results, the first pilot wellhead power plant is selected to be of a flash steam cycle type and with the output power of 5 MWe [2]. Similar turbines will be installed in the other sites of the Meshkin Shahr area as well. The final Meshkin Shahr geothermal power output will increase up to 100 MWe.

Due to the component specifications and working fluid characteristics, operation of the geothermal power plant is different from the thermal plant. After selecting the power plant components, correct operation through the thermodynamic parameters control is of high importance. Using both scientific research and geothermal power plant experience, it is possible to determine the optimal operational parameters. The purpose of this paper is to study the effect of the key parameters on the performance of a flash steam cycle power plant.

Methodology

Flash steam cycles

Flash steam plants are the most common type of geothermal power generation plants in operation today. They use water at temperatures greater than 182 °C that is pumped under high pressure to the power generation equipment at the surface. Upon reaching the generation equipment the pressure is suddenly reduced, allowing some of the hot water to convert or “flash” into steam. This steam is then used to power the turbine/generator units to produce electricity. The remaining hot water which is not flashed into steam, and the water condensed from the steam in the condenser is generally pumped back into the reservior.

The wellhead power plants are installed very close to the well (Fig. 4) [3]. The outlet mixture of steam and water from the well enters the wellhead separator. In the separator water droplets are separated from the steam. The steam passes through the steam dryer before it enters the steam turbine. The outlet steam from the turbine vents to the atmosphere. The saturated water drains from the turbine. This type of power plant generally has low output power.

The single and double stage flash steam power plants are installed far from the well. The outlet steam or mixture of the steam and water from the wellhead separator is transferred to the power plant through a pipe line. This type of power plant is known as the geothermal central power plant. A single stage flash steam cycle is shown in Fig. 5. This type of power plant has additional equipment such as condenser, cooling tower, and ejector for non condensable gases. In a double flash steam cycle, the outlet water from the high pressure flash vessel has considerable amount of energy. Therefore, it is delivered to a low pressure flash vessel and the resulting steam feeds the low pressure turbine (Fig. 6).

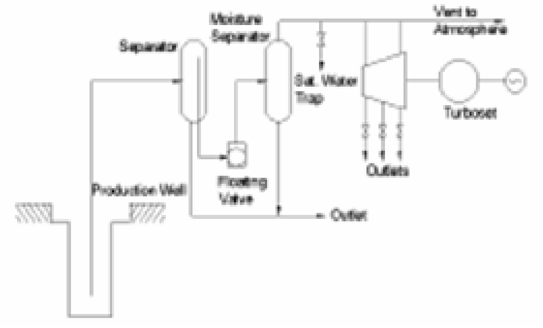

Fig.4 The schematic of a wellhead unit

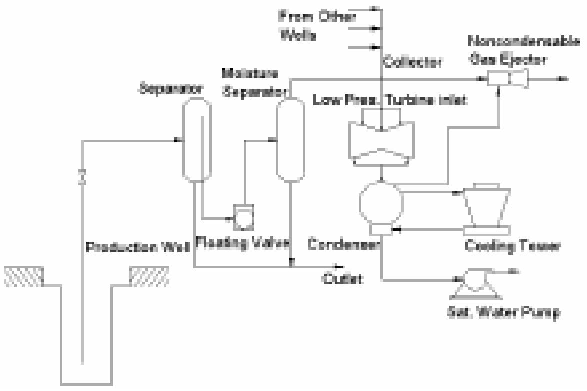

Fig. 5 The single stage flash steam cycle schematic

The flash vessel pressure effect

Separator or the flash steam vessel is one of the important parts of a flash steam cycle. It separates steam from water. Eq. (1) shows steam quality (steam to mixture of steam and water mass ratio) at the first stage flash vessel (X_1).

$$X_1 = \frac{h_o - h_w}{h_{1,fg}} \tag{1}$$

where, h_o is the enthalpy of the outlet water and steam mixture from the geothermal well which is delivered to the flash vessel, h_{w1} is the enthalpy of outlet hot water from the flash vessel and h1fg is the latent heat at the first stage flash vessel pressure. It is obvious that the output steam mass flow quantity from the flash vessel is the product of X_1 and the outlet fluid from the well. Therefore, in order to increase the output steam mass flow rate it is necessary to minimize the flash vessel pressure. In fact as the pressure decreases the hot water enthalpy (h_{w1}) decreases. Therefore, according to Eq. (1), X_1 increases which causes the steam mass flow rate to the turbine and the output power to increase. Steam quality in the second flash vessel (X_2) is calculated from Eq. (2)

$$X_2 = \frac{h_{w1} - h_{w2}}{h_{2fg}} \qquad (2)$$

where, h_{w1} is the enthalpy of outlet hot water from the first separator, h_{2fg} is the latent heat of outlet hot water from the first flash vessel and h_{w2} is the enthalpy of outlet hot water from the second flash vessel. If the pressure in the second flash vessel decreases, the steam mass flow which is delivered to the low pressure turbine increases similar to the first flash vessel. It should be noted that the following limitations arise when reducing the pressure in the first and second flash vessels.

1. By decreasing the pressure in the first flash vessel, h_{w1} decreases and according to the Eq. (2), X_2 and the inlet steam flow to the low pressure turbine decreases.
2. Since the output power of the turbine is a function of inlet pressure, by decreasing the pressure in the first and second flash vessels, the steam inlet pressure to the high pressure and low pressure turbines decreases. Therefore, the total turbine output power decreases.
3. If the flash steam pressure decreases to a value less than the allowable threshold, there will be air leakage in connecting pipes to the separators that causes finally the air entrance into the separators.

According to the above limitations, it is necessary to consider an optimal pressure for the flash vessels or separators. This value is usually 517 kPa for the first and 138 kPa for the second flash vessel [4].

The turbine inlet pressure effect

The turbine inlet enthalpy is a function of steam inlet pressure. Therefore, by increasing the steam inlet pressure, the turbine output power increases. The turbine output work is calculated from Eq. (3).

$$\mathbf{W_1=h_1-h_2} \qquad \mathbf{(3)}$$

Where h_1 and h_2 are the inlet and outlet steam enthalpies respectively. The turbine outlet enthalpy is a function of condenser pressure The only thermodynamic parameter that can be changed in the steam turbine is the inlet enthalpy. It can be enhanced by increasing the inlet pressure. The turbine pressure is usually designed for the final pressure at the end of its design life which is around 20-30 years. The optimal pressure design is based on the geothermal turbine operational experience. For example, the existing experience shows that for a turbine with the initial 1.3 MPa inlet pressure, the selection of very high values for the inlet pressure is not suitable. The high pressure causes the geothermal resource to exhaust before the machine life ends up that is not economical. Therefore, the pressure limitations should be considered for the geothermal turbine. This is usually 448 kPa for high pressure and 103 kPa for low pressure turbines [4]. Choosing low pressures will also increase the electricity generation cost

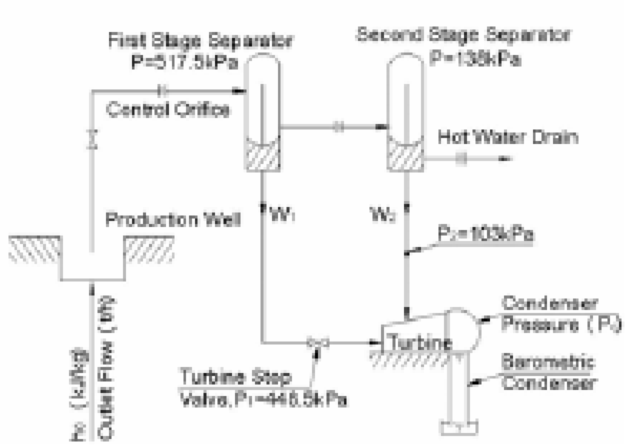

Fig.6 The double stage flash steam cycle model with the selected pressures

The condenser pressure effect

The turbine outlet enthalpy is a function of condenser pressure. Therefore, decreasing the turbine outlet enthalpy causes the turbine output work to increase (Eq. 3). Also by increasing the condenser pressure, the turbine steam rate (T.S.R) increases. This can be calculated using Eq. (4).

$$T.S.R = \frac{3600}{\left[(A.H.D)*0.85\left(1-\frac{w}{2}\right)-17.43\right]0.95} \qquad (4)$$

Where T.S.R. is the ratio of the required steam mass flow rate for delivering 1 kWh of electrical power, A.H.D is the adiabatic heat drop between the inlet and outlet turbine pressure and W is the mass ratio of water to the steam and water mixture at the turbine outlet

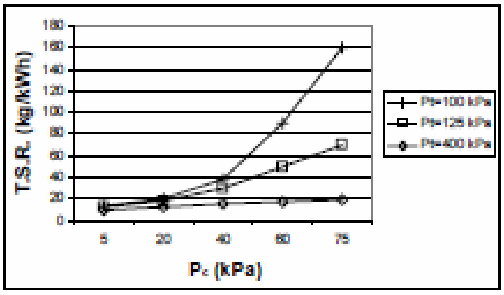

Fig. 7 Turbine Steam Rate versus condenser pressure (Pe) at different turbine inlet pressure (Pt)

Fig. 7 shows that by increasing the condenser pressure, the turbine steam rate increases which causes the output turbine power to decrease

$$W_t = \frac{1}{T.S.R.} \qquad (5)$$

The above relationship is more tangible at the higher inlet pressures. In fact at P_t = 400 kPa, by increasing the condenser pressure T.S.R increases rapidly. Therefore in order to increase the turbine work, condenser pressure should be reduced. However, there are the following limitations in the reduction of condenser pressure:

1. The turbine outlet loss increases by reduction of the condenser pressure. In fact reduction of condenser pressure decreases the steam quality or increases the water droplets at the turbine exhaust. These droplets will create a drag force which tends to reduce the turbine output power.

2. The droplets will be also responsible for erosion of the turbine last stage blades.
3. Further reduction of the condenser pressure, will cause the water outlet from condenser to freeze.

Therefore based on the above limitations the condenser optimal pressure range is selected from 6.9 kPa to 13.8 kPa.

The geothermal fluid enthalpy effect

The geothermal fluid enthalpy (h_0) is one of the important parameters in flash steam cycle operation. If one chooses the well outlet mass flow rate as 10 t/h and the pressures according to the data in Fig. 8, the turbine output power is calculated as the following:

$$WT_a = \frac{W_1}{(T.S.R)_1} + \frac{W_2}{(T.S.R)_2} \qquad (6)$$

where W_1 is the product of X_1 and well outlet mass flow rate, W_2 is the product of X_2 and well outlet mass flow rate, $(T.S.R)_1$ and $(T.S.R)_2$ are high pressure and low pressure turbines' steam rate respectively. The power potential is calculated from the following equation:

$$M = \frac{W_{Ta}}{\dot{m}_w} \left(\frac{MWh}{1000\ t}\right) \qquad (7)$$

The power potential is defined as the amount of electricity generation per geothermal well outlet fluid mass flow rate. The thermal efficiency is also calculated from the following equation:

$$\eta_{th} = \frac{M * 3.6}{h_o} \qquad (8)$$

Results and Discussion

In this part of paper we discuss the relation between power potential and the efficiency as a function of the geothermal outlet fluid enthalpy for the single and double stage flash cycles [5]. Fig. 8 shows the power potential versus the geothermal outlet fluid enthalpy for a single stage flash steam cycle at different condenser pressures. It is clear that if the geothermal outlet fluid enthalpy increases the power potential will increase. The increase in power potential means the maximum usage of the geothermal fluid for the production of power. In fact, the geothermal resources with higher outlet fluid enthalpy will produce more power for the same geothermal fluid mass flow rate. Fig. 9 presents the same curve for a double stage flash steam cycle. According to these figures, the power potential in the double stage cycle is more than single stage at the same h0. This effect is more intensified at low h0. However, both curves are overlapped for h_0>2747.6 kJ/kg. This is due to the fact that the geothermal fluid from the well is at the steam condition. This means that there is no need for the second separator.

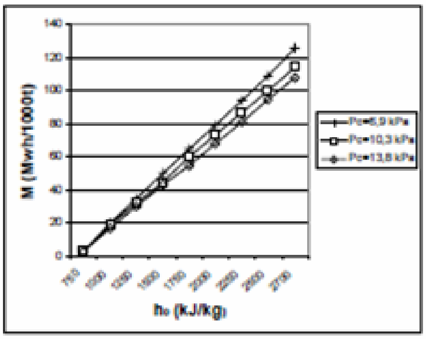

Fig. 8 Power Potential versus geothermal fluid enthalpy at different condenser pressures for a single stage flash steam cycle

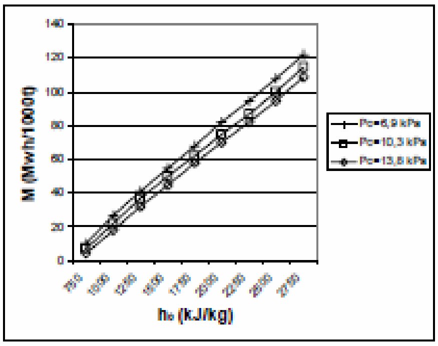

Fig. 9 Power Potential versus geothermal fluid enthalpy at different condenser pressures for a double stage flash steam cycle

Fig. 10 shows the relationship between h_0 and thermal efficiency of the single stage flash steam cycle. It shows that by increasing the h0, the thermal efficiency increases. Nevertheless, the efficiency slope gradually decreases at the higher enthalpies. At the low enthalpies, the thermal efficiency varies significantly with the h0 variation. Therefore, the efficiency of the power plants with higher geothermal outlet fluid enthalpy is higher than the efficiency of power plants with lower h_0. Fig. 11 shows the same curve for a double stage flash steam cycle. According to this figure, at low outlet fluid enthalpies, the thermal efficiency of the double stage cycle is more than efficiency of the single stage cycle at the same h0. Moreover, both curves are overlapped for h_0>2747.6 kJ/kg as explained before. According to Figs. 10-11, if the condenser pressure is reduced the efficiency of the geothermal power plant is increased. Therefore by the selection of the minimum allowable condenser pressure, higher thermal efficiency is achieved. This fact should be considered in the operation of geothermal power plants. In fact one may avoid the increase in the condenser pressure and the reduction in the efficiency of the power plant by the control and monitoring of this critical parameter.

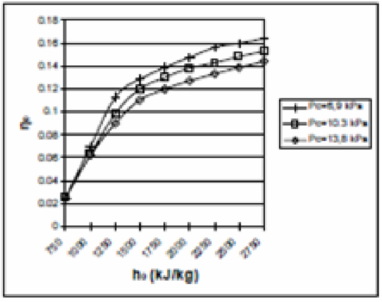

Fig. 10 The thermal efficiency versus geothermal fluid enthalpy at different condenser pressures for a single stage flash steam cycle

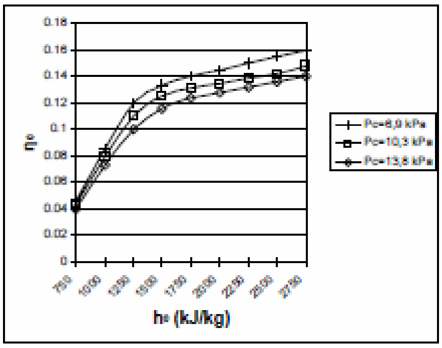

Fig: 11 The thermal efficiency versus geothermal fluid enthalpy at different condenser pressures for a double stage flash steam cycle

Conclusion

In this article the geothermal flash steam cycle was studied. It has been found that this type of geothermal power plant is appropriate to be utilized in Iran. Based on the turbine lifetime and geothermal source limitations, the optimum inlet pressure for high and low pressure turbines were determined to be 448 kPa and 103 kPa respectively. Due to separator limitations, the optimum pressure for first stage and second stage flash vessels were determined to be 517 kPa and 138 kPa respectively. It should be noted that if those parameters deviate from their optimum values, they will adversely affect the cycle performance.

The condenser pressure is an important parameter that affects the output power, power potential and thermal efficiency of the cycle. Considering the inherent limitation of this parameter as well as the turbine limitation, the minimum allowable condenser pressure should be chosen to produce maximum efficiency and output power. This pressure should be always controlled during the power plant operation. The geothermal outlet fluid enthalpy (h_0) has also a direct effect on power potential and thermal efficiency and its reduction during operation will reduce power potential and thermal efficiency. The thermal efficiency and output power factors should be monitored during the operation of the flash steam cycle for the economical utilization of the cycle.

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